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"Socially just" support mechanisms for the promotion of renewable energy sources in Greece

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ABSTRACT

Although development of renewable energy sources (RES) projects is essential for the Greek national economy to revive, cut downs of public spends in Greece may equally well extend to affect RES support mechanisms. In this context, an integrated cost–benefit analysis is currently undertaken concerning RES investments in the Greek electricity sector. More specifically, social support compared with financial benefits accruing from such energy stations reveals hidden imbalances that urge for the reform of the current support status. Examination of representative case studies currently provided considers the three most widespread RES, i.e. wind energy, hydropower and solar energy, with special emphasis given on the determination of break-even feed-in-tariffs (FITs) and the comparison of life-cycle electricity production cost between RES and conventional power stations.

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Contents

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1. Introduction

Climax of economic crisis [1] in Greece during the recent period affects among others the electricity generation sector. To this end, due to the limited available financial resources and the significant cut down of public spends, the "social just" of public funds used by private investors for the development of renewable energy sources (RES) based projects is strongly questioned. On the other hand, development projects are essential for the national economy to revive, while the problem becomes even more serious for the local energy authorities in case that the obligation of Greece to comply with certain RES and CO_2 targets [2,3] is also considered. More specifically, gross electricity generation based on RES, requested to reach 40% of the respective national gross electricity generation by 2020, has only been kept within the range of a long-term 10–13% (Fig. 1), mainly configured by the participation of large hydro generation. At the same time, according to the latest official data [4], RES electricity generation reached during 2009 a total amount of only 8 TWh, with the respective national total exceeding 65 TWh.

In this context, taking into account that the mean annual increase of electricity generation in the forthcoming years is expected – due to the impacts of economic crisis [5,6] – to drop to 1–1.5% or even turn negative (opposite to the long-term mean annual increase of approximately 3.5%, see also Fig. 1), the RES electrical energy production to be achieved by the year 2020 should according to the estimations [7] exceed 25 TWh and may reach 30 TWh, i.e. more than three times the current gross RES electricity generation.

In this regard, in order to achieve the national RES targets and structure a secure and at the same time socially fair investing environment that may attract private funds, an integrated cost–benefit analysis is currently developed, aiming at the reform of RES State support in Greece [8], following also the ongoing discussion in several countries regarding the effectiveness of State support measures [9–15]. To this end, a number of representative case studies, covering both the mainland and the island region of the Greek territory are currently examined, focusing on the three most widespread RES of the local market, i.e. wind energy, hydropower and solar energy.

2. RES contribution in the Greek electricity generation system

The electricity generation system of Greece is divided in two main areas, i.e., the mainland and the island subsystem. As far as the mainland (national) electricity grid is concerned, centralized power generation based mainly on the indigenous lignite reserves should be considered. On the other hand, the numerous isolated electrical grids of the island region (35 autonomous power stations (APSs) operating), on top of the Crete island, rely mainly on oil imports [16]. More precisely, national long-term dependence on fossil fuels is presently reflected by the employment of approximately 6.1 GW of steam turbines, principally using local lignite reserves [17,18] as well as heavy oil imports, 2.3 GW of combined cycle power plants using imported natural gas (NG), and a total of 1.3 GW of oil based-generation (gas turbines and internal combustion engines), mainly used for covering the greatest share of electricity consumption in the Aegean island micro-grids [16].

Additionally, the mainland electricity grid is also supported by the operation of large hydropower plants [19] that exceed 3 GW and is used as peak shaving units (including two pumped hydro units of almost 700 MW). Besides that, the contribution of RES mostly derives from wind energy applications (currently over 1.65 GW) [20], while a small proportion corresponds to small-hydro [21], biogas and industrial waste installations (a total of 350 MW), with photovoltaic (PV) plants approaching 1 GW.

Following, as far as the energy contribution of RES installations is concerned, as already mentioned, of critical importance is the operation of large-hydro plants that have during the past allowed for the total RES share to reach a maximum of 14%, while the respective wind energy share is at the moment equal to approximately 5% of the total gross electricity production. On the other hand, existence of excellent RES potential [16,19] in many regions (Fig. 2) and especially in island areas (except from hydro), further aggravates the situation encountered, e.g. excellent wind potential met in many islands remains largely unexploited [22]. In fact, if excluding certain island areas (e.g. Crete, where the installed wind power capacity has exceeded 160 MW), a maximum of 10–15% of RES energy contribution is met across the Aegean Sea, although the extremely high electricity production cost of these grids [16] (even approaching 1 €/kWh; Fig. 3) justifies the installation of large-scale RES capacity, even if energy storage or demand response measures are required to sustain demand satisfaction [23–25]. The use of lignite on the contrary is the main factor for the configuration of the mainland marginal production cost, yielding that half the year the cost of electricity is kept under 70 €/MWh and 90 €/MWh for the 2 years examined in Fig. 4, depending on the specific year's annual fuel mix. Nevertheless, if the 2020 national target is to be achieved, the

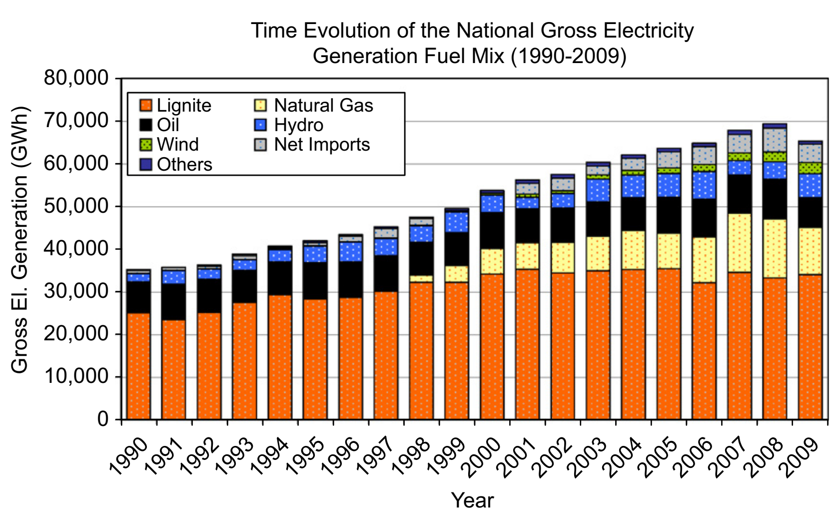

Fig. 1. Time evolution of the Greek electrical fuel mix.

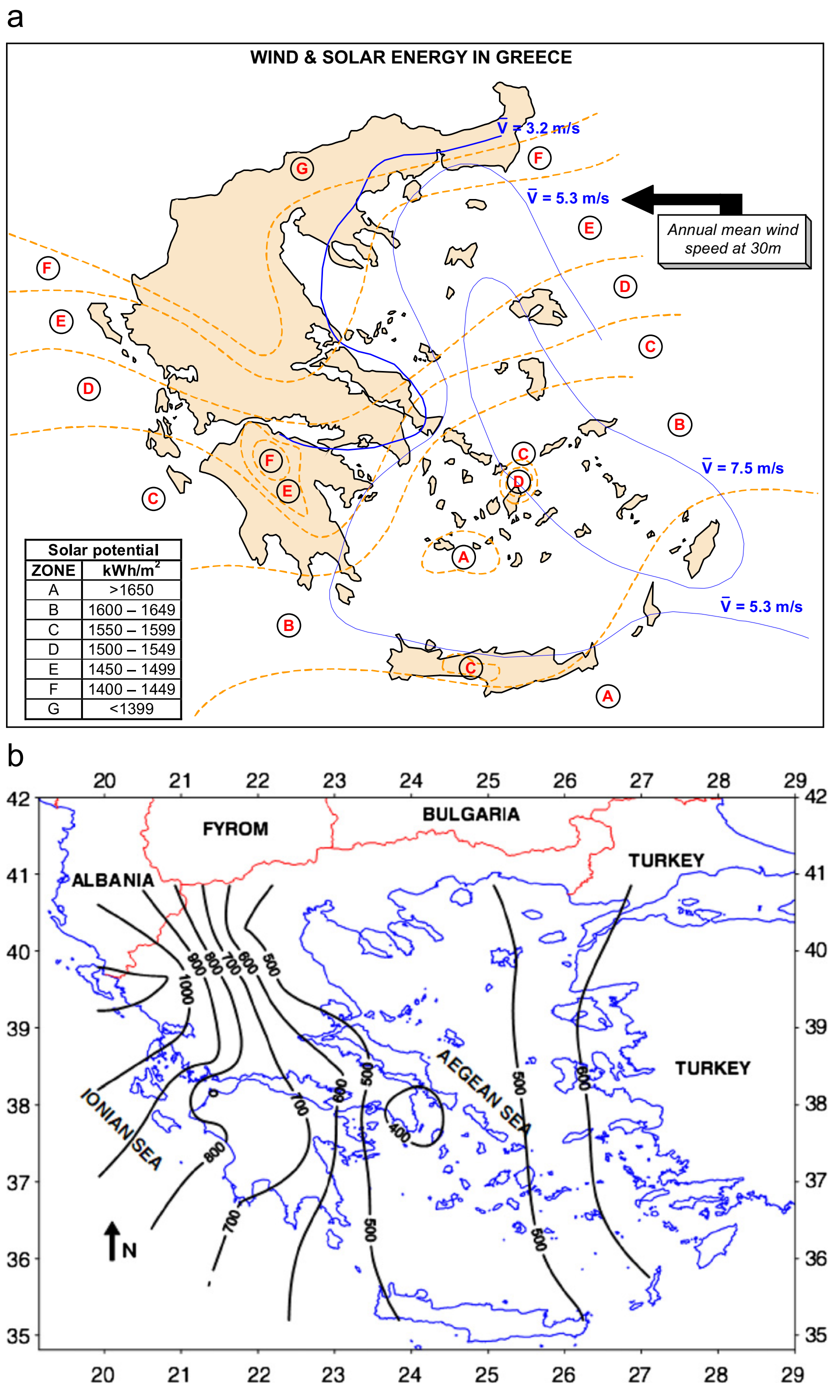

Fig. 2. Aspects of the wind–solar (a) and hydro (annual mean precipitation values in mm H_2O for the 1950–2001 period) (b) potential in Greece.

role of lignite should be downgraded, with estimations [7] concerning RES contribution to the national gross electricity generation of the time yielding approximately 35%. That means that more than 25 TWh of RES production per annum should be achieved, with the additional RES capacity required expected to range between 7 and 8 GW_e. In terms of cost, the numbers mentioned above correspond to the investments that may reach 10 billion Euros which according to the current status of support mechanisms imply State support in the order of 3–4 billion Euros.

Realizing the magnitude of investments as well as the magnitude of public spends required to finance the respective projects, the question of the social support repayment by the operation of such RES power stations should be answered. In this context, an integrated cost–benefit analysis is required to designate imbalances, attributed either to the side of the society (i.e. benefits accruing from the operation of RES projects exceed public spends for their support) or to the side of the RES developers (i.e. social support offered to RES projects cannot be compensated).

3. Social support offered to RES-based power stations

3.1. Energy and power production of RES stations

Installation and operation of a RES power station target first at the maximum exploitation of the local RES potential through the generation of electrical energy "E" and second at the support of the local electricity grid via the provision of power "N_{max}".

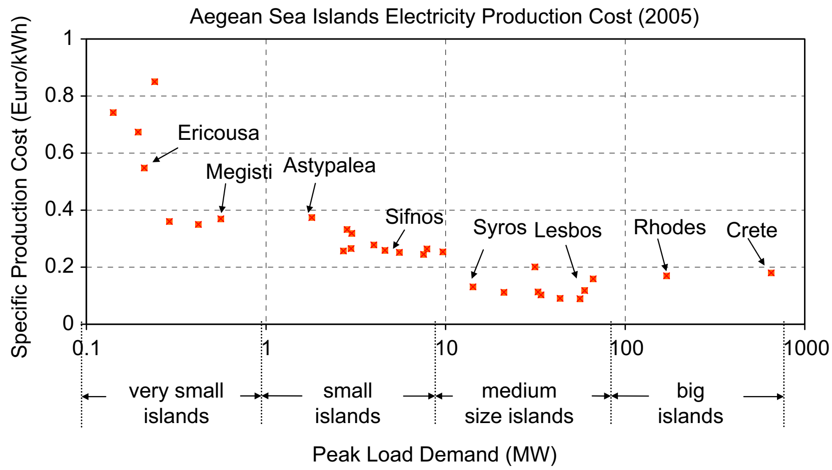

Fig. 3. Classification of the Aegean islands' electricity production cost by scale.

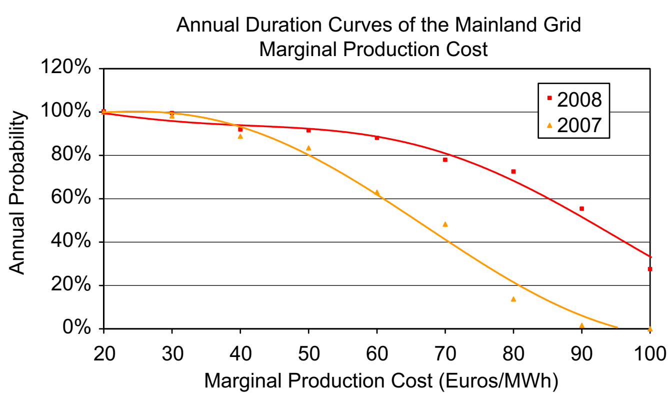

Fig. 4. Duration curves of the marginal electricity production cost for the Greek mainland.

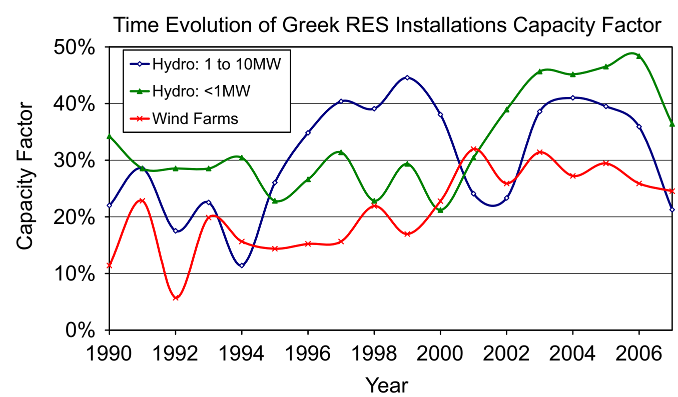

Fig. 5. Time evolution of the mean annual CF for wind and hydropower applications in Greece.

Concerning the first, the energy yield of a RES-based power station (rated power "N_0") is normally expressed via the following relation:

$$E = 8760 \cdot CF \cdot N_0 - \delta E \quad (1)$$

where "*CF*" is the corresponding capacity (or utilization) factor of the installation and "δE" describes the line transmission and transformation losses, as well as any self-consumption of the power station on an annual basis. More specifically, "*CF*" can be expressed as the product of the mean technical availability factor "Δ" and the mean power coefficient "ω" of the installation [26], i.e.

$$CF = \Delta \cdot \omega \quad (2)$$

The mean power coefficient "ω", expressing the yearly-averaged energy production during an hour per kW of nominal power of the station, takes into account the local RES potential and the capability of the installed equipment to exploit it. Accordingly, the technical availability factor "Δ" is associated with the period of the year that the RES-based power station is fault- and maintenance-free, taking also into account the interaction with the local electrical network and the corresponding absorption of energy yield.

In this context, in Fig. 5 one may obtain the time evolution of "*CF*" for wind parks and small hydropower stations operating in the Greek territory. According to the data presented, it accrues that wind parks of the Greek region operate at a long-term mean annual "*CF*" of 30%, with the respective value for small hydropower installations estimated to exceed 35%. Furthermore, although the operational experience recorded for PV installations is comparatively limited, rough "*CF*" values for the Greek territory range between 15% and 20%.

Following, due to the intermittent or even stochastic behavior of RES power stations [27], the resulting guaranteed power output "N_g" provided to the local grid is configured by a mean annual percentage "σ" of the respective maximum power output "N_{max}", defined by the 2244/94 Law, e.g. $\sigma = 0.5$ for wind parks i.e.

$$N_g = \sigma \cdot N_{max} \quad \text{where} \quad N_{max} \le N_0 \quad (3)$$

3.2. Brief presentation of the initial cost subsidy opportunities

The Greek State, following the general EU directions, characterizes RES-based investments as environmentally friendly energy solutions that may contribute to national development. In this context, it encourages implementation of similar projects by private investors since 1985/1994 (Laws 1559/85 and 2244/94) and provides actual support on the basis of several financing schemes [3,28,29]. More precisely, all the RES-based projects may be approved for subsidy under several development laws (since 1982), according to which every similar effort could be subsidized by a remarkable portion "γ" of its initial capital to be invested "IC_0". To this end, "γ" takes values from 30% to even 55% in special cases. Besides that, the State also guarantees the loan of the potential investor, thus contributing directly in covering the corresponding capital cost, while alternatively one RES-based

project may be also submitted for financial support to the National Competitiveness Program (EPAN), operated by the former Ministry of Development and the EU (FTP6/FTP7). For all these cases the private investor takes advantage of a remarkable contribution on the initial capital to be invested "IC_s", which may be expressed as

$$IC_s = \gamma \cdot IC_0 \tag{4}$$

thus, the first part "p_1" of the specific financial support (per kWh/MWh of electricity produced during the year "j", i.e. "$E_{(j)}$") provided to the RES power station via the initial cost subsidy can be expressed using the following relation:

$$p_{1(j)} = \frac{IC_s \cdot (1+i)^j}{n_{\max} \cdot E_{(j)}} = \frac{\gamma}{n_{\max}} \cdot \frac{IC_0}{E_{(j)}} \cdot (1+i)^j \tag{5}$$

where "$n_{\max}$" describes the service period of the installation and the term $(1+i)^j$ is used to transfer the value of the capital cost subsidization at the specific year "j", on the basis of the corresponding capital cost index "i".

3.3. The feed-in-tariff (FIT) mechanism

Another, even more supportive mechanism of RES-based applications, is the so-called "feed-in tariff" (FIT), used in several countries [30–32] in order to compensate for the electricity provided to the grid by RES-based power stations. What the term actually describes is a per kWh payment for electricity produced by RES, configured mainly on the basis of technology, geographical location and installation size [33]. High FITs are usually provided to less cost competitive and less mature technologies in order for innovation to be encouraged, while similarly, less developed locations such as isolated island grids and smaller scale applications are usually favored with higher prices. At the same time, reinforcement of the FIT mechanism is guaranteed on the basis of Power Purchase Agreements (PPAs). PPAs comprise legal contracts between the RES electricity generator and the power purchaser (i.e. the Greek National Electricity System Operator or the Public Power Corporation for the islands) and are often regarded as a key element for the potential investor to secure project financing.

According to the scheme presented above, the National Electricity System Operator of Greece guarantees the absorbance of the RES-based electricity generation, in priority, for the next 10+10 years and for a predefined price "p_0" related with the electricity generation cost of the entire system. Regarding RES applications in Greece, prices are configured according to the latest re-assessment (February 2010) of the 3468/2006 Law rates, see also Table 1, while what should also be mentioned is the obligation of the local network manager to absorb the RES-originated electricity generation, excluding the case that the technical minima of the system are violated [34]. On the other hand, in island autonomous electrical grids, severe RES energy participation limits (especially for wind power) set by the local network operator – in an attempt to protect the grid reliability and stability – have up until recently constrained the participation of RES energy at the levels of 10–15%. Contrariwise, excellent RES potential in most of these areas (Fig. 2) in combination with the extreme electricity production cost of the oil-based power stations, at the range of 250 €/MWh on average (Fig. 3), still challenge new RES investments in these locations.

In this context, compensation of RES energy produced and delivered to the local grid (per kWh/MWh) comprises the second component of social support for RES investments "p_2" (Eq. (6)), being actually based on the station's annual revenues "R" (Eq. (7))

$$p_{2(j)} = \frac{R_{(j)}}{E_{(j)}} = p_0 \cdot (1+e)^j + \frac{1}{CF_j}\left(\frac{\sigma}{8760} \cdot \sum_{l=1}^{12} \frac{\mathrm{N}_{\max_l}}{N_0}\right) \cdot p_N \cdot (1+e_N)^j \tag{6}$$

The total revenues for a specific year "j" – resulting from the operation of a RES power station – derive from the energy production sold to the national/local electrical grid, while it should be mentioned that for certain RES projects implemented before the Law 3468/2006 there was a monthly compensation for the power added to the local network, only for the interconnected electrical system. Thus, the income of the RES power station during the year "j" can be given from the following equation:

$$R_{(j)} = E_j \cdot p_0 \cdot (1+e)^j + \left(\sigma \cdot \sum_{l=1}^{12} \mathrm{N}_{\max_l}\right) \cdot p_N \cdot (1+e_N)^j \tag{7}$$

where "p_0" and "p_N" are the energy price (€/kWh) and the power remuneration per month (€/kW/mo, currently zeroed) at the start of the operation of the investment. Also, "e" and "e_N" are the corresponding electricity price and electrical power compensation (average) annual escalation rate, respectively, while "$N_{\max}$" is the maximum output power of the station for every month of the year and "σ" is the average power contribution factor of the RES power station to the local grid, e.g. $\sigma = 0.5$ for wind parks.

3.4. Other forms of RES support

Finally, as already implied, the intermittent or stochastic behavior of RES power stations may induce both instability and security of supply problems, especially in the case of small-scale island networks where grid imbalances are harder to handle. Furthermore, priority given to the absorption of RES energy production forces thermal power stations to adjust their operation accordingly [34].

Hence, there is an indirect support offered to RES power stations by both the electricity grid that addresses intermittent/stochastic energy production issues and the thermal power stations that are obliged to adjust to a different operation pattern (other than the optimum). Thus, although hard to quantify, the

Table 1
Old and new FITs concerning RES power stations in Greece.

Updated FITs (2/2010)

Wind power			PV applications				Hydropower	
Mainland	Islands	Offshore	Mainland <5 MW	Islands <5 MW	Mainland >5 MW	Islands >5 MW	Mainland <15 MW	Islands <15 MW
87.85	99.45	104.85	264.85	284.85	244.85	264.85	87.5	99.45

Old FITs (2006)

Wind power		PV applications				Hydropower	
Mainland	Islands	Mainland <100 kW	Islands <100 kW	Mainland >100 kW	Islands >100 MW	Mainland <15 MW	Islands <15 MW
73.00	84.60	450.00	500.00	400.00	450.00	73.00	84.60

third component of social support "p_3" (Eq. (8)) is actually referring to the aforementioned auxiliary services

$$p_{3(j)} = p_{aux_j} \tag{8}$$

4. Financial benefits from the operation of RES-based power stations

4.1. Substitution of the fossil-fuel based power stations' operation

Substitution of the already operating thermal/autonomous power stations (TPSs-APSs), either in the mainland or in island regions, suggests the first source of financial benefits for the operation of RES-based power stations. In this context, as previously implied, the specific benefit component is of special importance for island areas, especially those of small scale [35]. Electricity generation in these isolated electrical grids is largely based on volatile-priced oil imports and relatively outmoded generators that require considerable maintenance [16]. As a result the electricity production cost is quite high (Fig. 3), thus providing extra motives for the installation of on-site RES-based power stations. Contrariwise, the mainland electricity generation yields a considerably lower electricity production cost, mainly due to the exploitation of "cheap", indigenous lignite reserves [17] (Fig. 4), in many cases beating the respective production cost of RES installations. On the other hand, capacity of the interconnected system permits large-scale penetration of RES [36], required to achieve the European targets. Concluding, the savings of the local electricity grid are mainly configured by the operating cost "c_f" of the TPS/APS replaced (mainly fuel and lubricants saving, service avoidance etc.) and a small ($\approx$5%) percentage "ξ" of the constant cost reduction (e.g. service period prolongation of the local TPS/APS), i.e.

$$c_{t(j)} = c_{f_{(j)}} + \xi \cdot \left(c_{\mathrm{TPS}_{(j)}} - c_{f_{(j)}} \right) \tag{9}$$

with "c_{TPS}" being the total electricity generation cost of the replaced TPS/APS.

4.2. Taxation fees

A second source of financial benefits concerns taxation, currently including both the annual tax paid on the basis of net cash flows and the provision of a fixed revenues' fraction to the municipality where the RES power station operates. More precisely, according to the current legislation framework (Law 2773/99) [3], a supplementary amount from the investment revenues "δr" (€/kWh or €/MWh) is directly transferred to local municipalities existing in the surroundings of the RES station, defined as a fraction "$\delta p.R_{(j)}$", where $\delta p \approx 2$–3%

$$\delta r_{(j)} = \frac{\delta p_{(j)} \cdot R_{(j)}}{E_{(j)}} = \delta p_j \cdot p_0 \cdot (1+e)^j \tag{10}$$

while in order to obtain a clear cut picture of the amount that a RES investment returns to the national economy, one should also estimate the corresponding annual tax paid "$\Phi_{(j)}$". Actually, "$\Phi_{(j)}$" describes the tax paid during the "j" year, mainly due to the revenues of the previous year $R_{(j-1)}$. According to the Greek tax-law, "$\Phi_{(j)}$" depends on the law-defined tax-coefficient "φ" (e.g. $\varphi = 30\%$), the net cash flow of the "j–1" year, the investment depreciations, as well as the financial obligations of the enterprise [26]. More precisely,

$$\Phi_{(j)} = \phi_{(j)} \cdot [R_{(j-1)} - \delta p \cdot R_{(j-1)} - FC_{(j-1)} - VC_{(j-1)} - CA_{(j-1)} - Var_{(j-1)}] \tag{11}$$

where "CA" describes the initial capital depreciation and may be simulated using a simple constant annual investment depreciation model as

$$CA_{(j)} = (1-\gamma) \cdot \left[\frac{IC_1}{n_1} + \frac{IC_2}{n_2} + \frac{IC_3}{n_3} + \frac{IC_4}{n_4} + \cdots \right] \tag{12}$$

with "IC_k" and "n_k" describing the initial cost and the corresponding (law-defined) amortization period of the "k" category of the investment capital (i.e. electrical, electronic, mechanical equipment, civil engineering works, managerial-consulting services, etc.).

Additionally, in Eq. (11) the term "*Var*" includes any additional cost not described by the other terms, like financial obligations, unexpected expenses, etc. (currently, however, taken equal to zero), while the terms "*FC*" and "*VC*" refer to the fixed and variable component of the maintenance and operation (M&O) cost, analyzed in Section 5. According to the above presented analysis, the total amount paid by the private investment "$\delta\varphi$" (€/kWh or €/MWh) on the basis of annual tax is estimated as

$$\delta\varphi_{(j)} = \frac{\Phi_{(j)}}{E_{(j)}} \tag{13}$$

while the overall taxation component "δt", including also the local municipality tax, is given on the basis of Eqs. (10) and (13) as

$$\delta t_{(j)} = \frac{\delta p_{(j)} \cdot R_{(j)}}{E_{(j)}} + \frac{\Phi_{(j)}}{E_{(j)}} = \delta p_j \cdot p_0 \cdot (1+e)^j + \frac{\Phi_{(j)}}{E_{(j)}} \tag{14}$$

4.3. Avoided social costs-I (fuel imports and carbon dioxide tax)

Furthermore, among the main benefits of the RES-based applications one may mention the imported fossil fuel reduction "δf" and the avoidance of carbon dioxide related taxes "δcd" [37], both included in the avoided social costs' (or social benefits') component.

Note that Greece imports annually more than 200 million barrels of oil equivalent (including NG, electricity etc.). In this context, the annual oil saving due to the operation of the RES power station may be estimated via the efficiency "η_d" of a typical TPS/APS and the corresponding specific calorific value "H_u" of the fossil fuel consumed using the following relation:

$$M_{f(j)} = \frac{E_{(j)}}{\eta_d \cdot H_u} \tag{15}$$

The corresponding annual cost savings due to the fuel imports avoidance may be calculated as

$$\Delta C_{(j)} = M_{f(j)} \cdot \zeta_j \cdot p_{\mathrm{fuel}_{(j)}} \tag{16}$$

with "p_{fuel}" being the average fuel price during the year "j" and "ζ" being the appropriate coefficient that relates, e.g. the diesel and heavy-oil quantities consumed with the corresponding imported crude oil quantities. Subsequently, the annual equivalent carbon dioxide emissions avoided due to the operation of RES power stations may be estimated using the corresponding carbon dioxide emission coefficient [37] of the replaced TPS/APS "ε_{CO2}" (e.g. 0.5–1.3 kg CO_2/kWh$_e$) as

$$\delta CO_{2(j)} = E_{(j)} \cdot \varepsilon_{CO_{2(j)}} \tag{17}$$

Hence, the carbon dioxide cost avoided is given via the equivalent average specific price "t_{CO2}" using the following relation:

$$\Delta T_{(j)} = \delta CO_{2(j)} \cdot t_{CO_{2j}} \tag{18}$$

4.4. Avoided social costs-II (other externalities)

Finally, investigating the environmental and macroeconomic impacts of the RES-based power stations one should also take into

consideration several important parameters, described in various international [38–42] and national [43] studies, like the air pollution reduction, the infrastructure improvement, the GDP increase, the energy supply security as well as the noise and visual impacts [44], etc. In this context, in the present analysis one eventually takes into consideration the so-called "externalities" contribution by introducing the corresponding net external cost "c_{ex}" (€/MWh) in the proposed analysis [45]. As a result of the analysis undertaken in Sections 4.3 and 4.4, the total social benefits for each MWh of electricity produced by the RES based power station "δx" can be described by the following relation, i.e.:

$$\delta x_{(j)} = \delta f_{(j)} + \delta cd_{(j)} + c_{ex_{(j)}} = \frac{\zeta_j \cdot p_{\text{fuel}_{(j)}}}{\eta_d \cdot H_u} + \varepsilon_{\text{CO}_{2(j)}} \cdot t_{\text{CO}_{2(j)}} + c_{ex_{(j)}} \tag{19}$$

5. Electricity production cost of RES-based power stations

According to previous analyses by the authors [26,46], the present value of the investment cost of a RES installation (after –j years of operation) is a combination of the initial cost and the corresponding M&O cost. The initial cost includes the market price of the electromechanical equipment (usually ex-works), the civil engineering activities and the corresponding balance of plant (BOP) cost. Thus one may write

$$IC_0 = \text{Pr} \cdot N_0 + f \cdot \text{Pr} \cdot N_0 = \text{Pr} \cdot N_0 \cdot (1+f) \tag{20}$$

where "Pr" is the specific ex-works price (€/kW) of the technology used. Subsequently, "f" expresses the installation cost (e.g. electrical interconnection cost, access tracks, development cost, etc.), which is given as a fraction ($f \approx 5$–50%) of "Pr", with "$f.Pr.N_0$" being the BOP cost. Moreover, the M&O cost can be split into the fixed "FC" and the variable one "VC". Expressing the annual fixed M&O cost of the year "j" as a fraction "m_j" of the investment installation cost and assuming an average annual increase equal to "g_m", the value of "$FC_{(j)}$" is given as

$$FC_{(j)} = m_j \cdot IC_0 \cdot (1+g_m)^j = m_j \cdot \text{Pr} \cdot N_0 \cdot (1+f) \cdot (1+g_m)^j \tag{21}$$

while the respective cumulative M&O cost after –j years of operation is given – in present values – as

$$FC_j = m \cdot IC_0 \cdot \left[\frac{1+g_m}{1+i} + \left(\frac{1+g_m}{1+i}\right)^2 + \cdots + \left(\frac{1+g_m}{1+i}\right)^{j-1} + \left(\frac{1+g_m}{1+i}\right)^j \right] \tag{22}$$

Finally, the variable M&O cost "VC" [26] currently neglected, mainly depends on the replacement of specific major parts of the installation, which may have a shorter lifetime than the complete power station and are normally replaced during certain years of the operational life of the installation. Using the above analysis and considering that the RES system operates for "j" years, one may estimate the corresponding total operational cost by combining the initial cost and the fixed and variable M&O cost, i.e.

$$C_j = IC_0 \cdot (1-\gamma) + FC_j + VC_j - Y_j \tag{23}$$

To this end, in Eq. (23) "Y_j" represents the residual value of the investment, attributed to amounts recovered at the "jth" year of the RES system service period (e.g. value of land or buildings after decommissioning, scrap or second hand value of equipment, etc.), along with the experience gained and the corresponding technological know-how.

Lastly, taking also into account the analysis presented in [47], concerning the current electricity marginal production cost "c_e", one gets the following Eq. (24), provided that the "VC" term of Eq. (23) is neglected and that the net present value of the investment becomes equal to the corresponding residual value (NPV$=Y_j$, where Y_j may be equal to zero) after –j years of operation, i.e.

$$c_e = \frac{(IC_0 \cdot (1-\gamma) + FC_j) \cdot (z-1)}{E \cdot z \cdot (z^j - 1)} \tag{24}$$

where "z" is given by the following equation:

$$z = \frac{1+e}{1+i} \tag{25}$$

and "e" is the mean annual escalation rate of electricity price, e.g. $e=3\%$.

6. Cost–benefit analysis

Using the analysis of Eqs. (1)–(6), the total support offered by the society to the RES station each time under investigation may be expressed on the basis of the "p_t" term (€ per kWh/MWh of electricity produced)

$$p_{t(j)} = p_{1_j} + p_{2_j} + p_{3_j} = \frac{R_{(j)}}{E_{(j)}} + \frac{\gamma \cdot IC_0 \cdot (1+i)^j}{n_{\max} \cdot E_{(j)}} + p_{aux} \tag{26}$$

In this context, the additional cost (or gain) of the national economy due to the operation of the RES power station instead of the TPS/APS is expressed via the following relation:

$$\Delta p_{(j)} = p_{t(j)} - c_{t(j)} \tag{27}$$

On the basis of Eq. (27), if "Δp" is positive the RES-based power station surcharges the national economy for every kWh/MWh produced, while in case that "Δp" is negative the power station saves the corresponding amount in comparison with the operation of the existing TPS.

On top of "Δp", of special interest is also the difference of the electricity production cost "Δc" between the existing TPS/APS and the RES station each time examined, which can also be directly compared with the corresponding FIT value so as to examine whether the RES station is favored by or favors the network operator, in strictly operationally financial terms

$$\Delta c_{(j)} = c_{\text{TPS}_{(j)}} - c_{e_{(j)}} \tag{28}$$

Finally, evaluation of the private RES energy investments from the local economy point of view should also incorporate, on top of the comparison of Eq. (27), the additional terms of Eqs. (14) and (19), thus one may write

$$\Delta p^*_{(j)} = p_{t_{(j)}} - c_{t_{(j)}} - \delta t_{(j)} - \delta x_{(j)} \tag{29}$$

where "Δp^*" provides the overall result of the cost–benefit analysis, which if zeroed (i.e. benefits of the station balance the society costs) on the basis of the FIT variation, may produce the break-even feed-in-tariff (BEFIT) value "$p_0{}^*$"

$$p_0 = p_0^* \Rightarrow \Delta p^*_{(j)} = 0 \tag{30}$$

In this context, if the BEFIT "p_0^*" is found greater than the existing FIT "p_0", the operation of the RES installation examined favors the local society without being fully compensated on the basis of FITs, while the opposite is valid in case that the BEFIT is lower than the existing FIT, i.e. the State provides FITs that surcharge the local economy in favor of RES promotion.

7. Application results for the Greek territory

7.1. Description of representative case studies

The developed cost–benefit methodology, presented in Section 6, is accordingly applied for a number of representative case studies, considering all three technologies under examination and

taking into account the differentiation of support mechanisms between both mainland/island and large/small scale installations.

In this context, the size of the installations examined is configured so as to both establish a comparison basis between different technologies of more or less identical capacity (large, medium and small scale projects) and draw the lines among the enforcement of different FITs. Furthermore, to obtain a first evaluation concerning the social performance of RES projects in the Greek territory, the areas of installation considered in each case mainly correspond to typical CFs (see also Fig. 5), characteristic of the already operating projects.

In the case of PV installations, however, due to the lack of adequate operating experience recorded in Greece, the high quality solar potential of the entire Greek region allows for the adoption of analogous CFs. According to the data of Tables 2 and 3, the case studies currently examined include areas of both mainland and island regions. More specifically, in the case of mainland, distinct examination is attempted between the indigenous lignite-based power production and the imported-NG-based electricity generation, while in the case of island regions, a large-scale and a medium-scale island are currently considered, allowing for the incorporation of different electricity system characteristics as well.

Table 2
Input data for wind energy and hydropower projects.

Problem input parameter	Wind mainland (lignite)	Wind mainland (natural gas)	Wind big island (e.g. Crete)	Wind small island (e.g. Anafi)	Hydro mainland (lignite)	Hydro mainland (natural gas)	Hydro big island (e.g. Crete)	Hydro small island (e.g. Anafi)
First installation cost subsidy "γ" (%)	30	30	40	40	30	30	40	40
Coefficient of power "ω"	0.3	0.3	0.35	0.35	0.29	0.29	0.29	0.29
Technical availability "Δ" (%)	95	95	90	90	90	90	90	90
Specific (reduced) ex-works price "Pr" (€/kW)	750	750	800	1000	1500	1500	1600	1700
Nominal power of the plant "N_0" (MW)	15	15	10	0.5	15	15	10	0.5
Installation cost coefficient "f" (%)	20.0	20.0	25.0	30.0	30.0	30.0	32.5	35.0
Fixed M&O cost coefficient "m" (%)	3.00	3.00	3.25	3.50	1.50	1.50	2.25	2.50
Annual increase rate of the fixed M&O cost "g_m" (%)	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Energy price (FIT) "p_0" (€/MWh)	87.85	87.85	99.45	99.45	87.50	87.50	99.45	99.45
Power compensation per month price "p_N" (€/MW mo)	0	0	0	0	0	0	0	0
Annual increase rate of energy price "e" (%)	5	5	5	5	5	5	5	5
Annual increase of power compensation price "e_N" (%)	5	5	5	5	5	5	5	5
Average power contribution factor to the local grid "σ"	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Taxation coefficient "φ" (%)	30	30	30	30	30	30	30	30
Share of revenues towards local municipalities "δp" (%)	3	3	3	3	3	3	3	3
Amortization time "n" (years)	10	10	10	10	20	20	20	20
Thermal power station efficiency "η_d" (%)	30	40	34	33	30	40	34	33
Fuel calorific value "H_u" (MJ/kg)	6	47	40	40	6	47	40	40
Imported fuel price "p_{fuel}" (€/bbl)	0	45	50	50	0	45	50	50
Carbon dioxide emission factor "ε_{CO2}" (kg/MWh)	1200	500	840	800	1200	500	840	800
Carbon price "t_{CO2}" (€/tn_{CO2})	15	15	15	15	15	15	15	15
Auxiliary service price "p_{aux}" (€/MWh)	0	0	5	5	0	0	5	5
Service period of the installation "n_{max}" (years)	20	20	20	20	35	35	35	30
Thermal power station operating cost "c_f" (€/MWh)	30	50	80	230	30	50	80	230
Service period prolongation coefficient ξ	0	0	0.05	0.05	0	0	0.05	0.05
Electricity production cost of TPS/APS "c_{tps}" (€/MWh)	70	100	160	500	70	100	160	500
Net external cost "c_{ex}" (€/MWh)	70	10	47.5	44	70	10	47.5	44

Table 3
Input data for PV projects.

Problem input parameter	Large scale-mainland (lignite)	Large scale-mainland (natural gas)	Large scale-big island (e.g. Crete)	Small scale-small island (e.g. Anafi)	Medium[a] scale-mainland (lignite)	Medium[a] scale-mainland (natural gas)	Medium[a] scale-big island (e.g. Crete)
First installation cost subsidy "γ" (%)	40	40	45	50	40	40	45
Coefficient of power "ω"	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Technical availability "Δ" (%)	95	95	95	95	95	95	95
Specific (reduced) ex-works price "Pr" (€/kW)	4000	4000	4000	4500	4200	4200	4200
Nominal power of the plant "N_0" (MW)	15	15	10	0,5	5	5	2
Installation cost coefficient "f" (%)	10.0	10.0	15.0	20.0	10.0	10.0	15.0
Fixed M&O cost coefficient "m" (%)	1.00	1.00	1.30	1.50	1.00	1.00	1.30
Annual increase rate of the fixed M&O cost "g_m" (%)	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Energy price (FIT) "p_0" (€/MWh)	244.85	244.85	264.85	284.85	264.85	264.85	284.85
Power compensation per month price "p_N" (€/MW mo)	0	0	0	0	0	0	0
Annual increase rate of energy price "e" (%)	5	5	5	5	5	5	5
Annual increase of power compensation price "e_N" (%)	5	5	5	5	5	5	5
Average power contribution factor to the local grid "σ"	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Taxation coefficient "φ" (%)	30	30	30	30	30	30	30
Share of revenues towards local municipalities "δp" (%)	2	2	2	2	2	2	2
Amortization time "n" (years)	15	15	15	15	15	15	15
Thermal power station efficiency "n_d"	30	40	34	33	30	40	34
Fuel calorific value "H_u" (MJ/kg)	6	47	40	40	6	47	40
Imported fuel price "p_{fuel}" (€/bbl)	0	45	50	50	0	45	50
Carbon dioxide emission factor "ε_{CO2}" (kg/MWh)	1200	500	840	800	1200	500	840
Carbon price "$\underline{t}_{CO2}$" (€/tn_{CO2})	15	15	15	15	15	15	15
Auxiliary service price "p_{aux}" (€/MWh)	0	0	5	5	0	0	5
Service period of the installation "$n_{\max}$" (years)	25	25	25	25	25	25	25
Thermal power station operating cost "c_f" (€/MWh)	30	50	80	230	30	50	80
Service period prolongation coefficient ξ	0	0	0.05	0.05	0	0	0.05
Electricity production cost of TPS/APS "c_{tps}" (€/MWh)	70	100	160	500	70	100	160
Net external cost "c_{ex}" (€/MWh)	70	10	47.5	44	70	10	47.5

[a] Plus extra case studies.

7.2. Cost–benefit analysis for representative case studies

Some preliminary cost–benefit results are given in Figs. 6 and 7, where one may encounter an analysis of State support (Fig. 6) and the respective analysis of benefits accruing from the operation of the RES power station for each case study examined (Fig. 7).

According to the results of Fig. 6, State support provided (see also Eq. (26)) to wind energy and hydropower projects does not exceed 130 €/MWh in all cases examined, while in the case of PV installations State support may even cap 350 €/MWh. Concerning wind energy, costs induced by the operation of such stations present only a slight differentiation and are more or less independent from the case study examined. However, financial support offered to island projects is clearly higher than the respective of mainland installations, due to both the different FIT and the different initial capital per kW invested (economies of scale imply higher specific price for smaller installations and installation areas of different infrastructure characteristics means variation of the first installation cost coefficient "f"), influencing the initial cost subsidy.

Similar are the results obtained for hydropower stations, with the higher cost case appearing for small-scale island installations (which are, however, limited due to poor water reserves of most

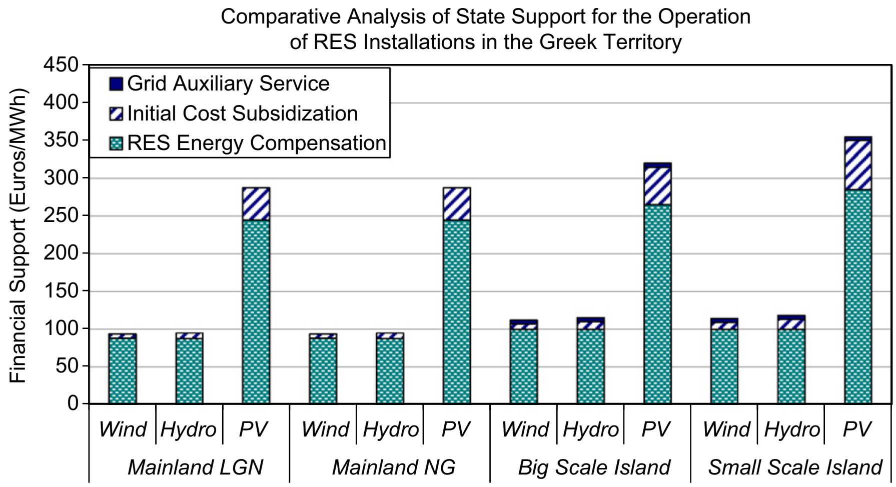

Fig. 6. Analysis of social support (costs) for representative case studies of the Greek territory.

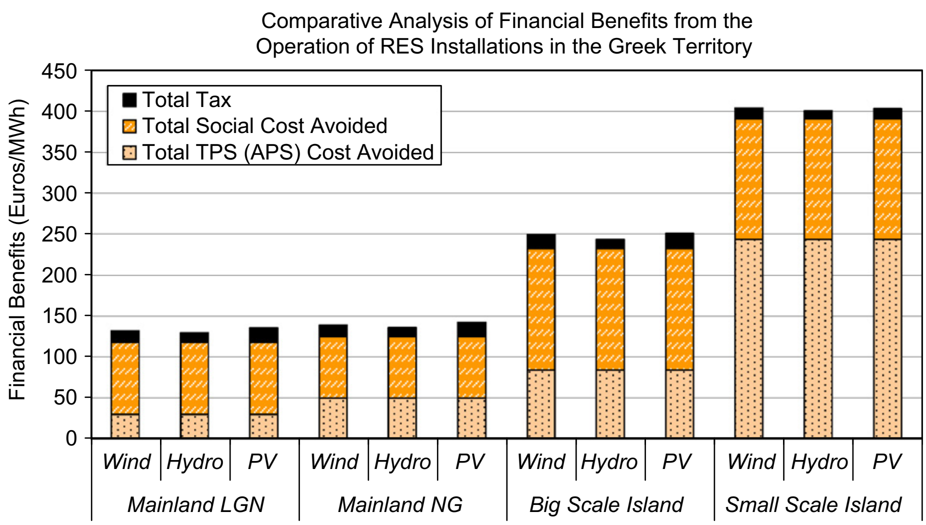

Fig. 7. Analysis of social benefits for representative case studies of the Greek territory.

Greek island regions) and the difference – in comparison with wind farms – imposed by the comparatively higher specific (reduced) ex-works price "*Pr*". Finally, the fact that PV stations are benefited by the higher social support is first owed to the favorable FITs and second to the heavy ex-work price of PV modules. Actually, as one may see, the compensation of solar energy production (i.e. the FIT offered) varies between 77% and 81% of the total social support, while the initial cost subsidy ranges from 17% to 22%, opposite to the wind energy and hydropower installations, where the respective maximum does not exceed 8.5% and 15.1%, respectively.

Following, results appearing in Fig. 7 give a first indication of financial benefits (see also Section 4) accruing from the operation of RES stations. A quick conclusion drawn from the figure encounters the indisputable financial advantage in case that similar stations are operated in small island regions of the Greek territory, i.e. where the remarkably high production cost of the oil-based electricity generation solutions avoided is actually much higher than (or even to) the total benefits obtained for mainland and big island applications. On the other hand, the most critical factor of mainland applications is the avoidance of social costs (Eq. (19)), the share of which maximizes in the case of lignite-based stations, exactly due to the heavier emissions entailed. Contrariwise, imports of NG imply higher operational cost for the respective stations (Eq. (9)), which is, however, kept lower than the operational cost of even big island electrical systems. Finally, taxation (Eq. (14)) is found in all cases examined below 8% of total benefits, largely depending on the FIT and the energy production variation configuring the revenues of the installation.

Besides that, the overall benefits are – in the case of mainland – found to be of the same magnitude for all technologies examined, i.e. within the range of 120–150 €/MWh, while the same behavior may be encountered for the island area as well, with values that are, however, somewhat higher (approximately 250 €/MWh and 400 €/MWh for big and small islands, respectively).

Finally, by directly comparing costs and benefits (Eq. (29)) for the cases examined, it becomes clear that all wind energy and hydropower applications investigated manage to compensate social support, especially in the case of island projects. Actually the marginal – in the case of mainland – net benefit that does not exceed 40 €/MWh, increases up to 285 €/MWh and 135 €/MWh for wind parks operated in small- and big-scale Greek islands, respectively. The exact opposite results are obtained in the case of PV applications, where the rather high State support allows for counterbalance between costs and benefits only in the case of small island regions. On the other hand, mainland PV applications demonstrate a net cost of more than 150 €/MWh, while in the case of big islands the net cost decreases to almost 70 €/MWh.

7.3. Breakdown of financial benefits

Following, in Figs. 8–10, a detailed analysis of financial benefits is provided based on the breakdown of taxation (Fig. 8), avoidance of TPS/APS operation (Fig. 9) and avoidance of social costs (Fig. 10). Taxes paid by the RES installations examined are directly related with investment revenues, mainly configured by the FIT price and the annual amount of energy production. As a result, there is a common pattern among all three technologies, i.e. a maximum amount of taxation is encountered in big island

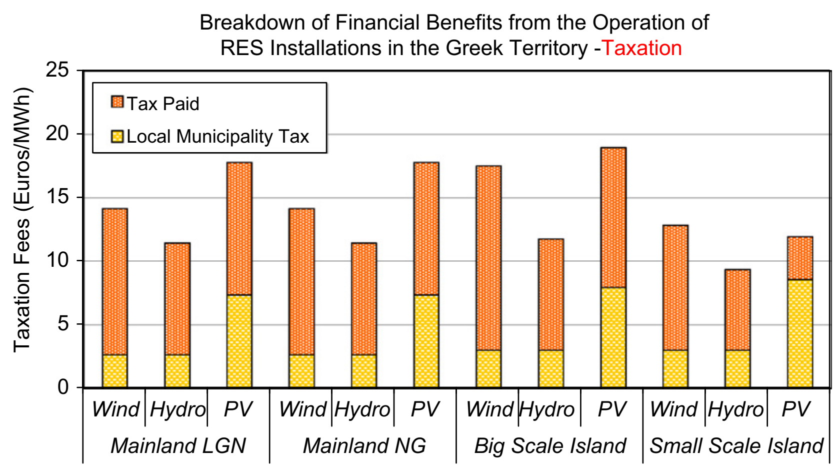

Fig. 8. Breakdown analysis of financial benefits from taxation for representative case studies.

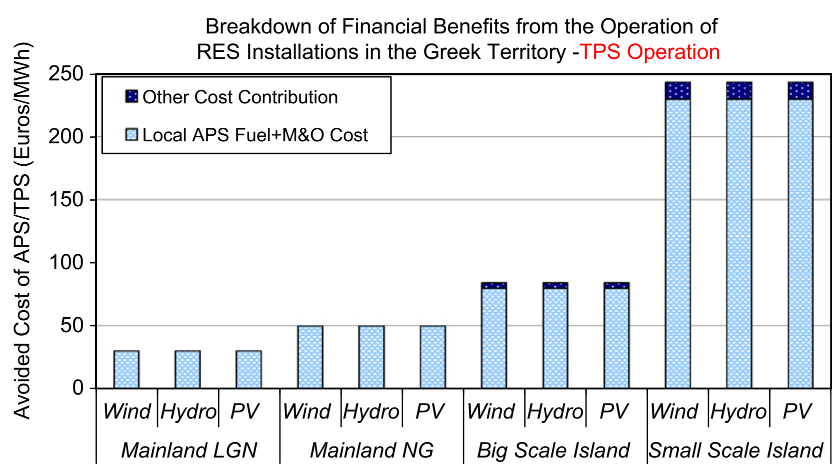

Fig. 9. Breakdown analysis of financial benefits from the avoidance of TPS/APS operation for representative case studies.

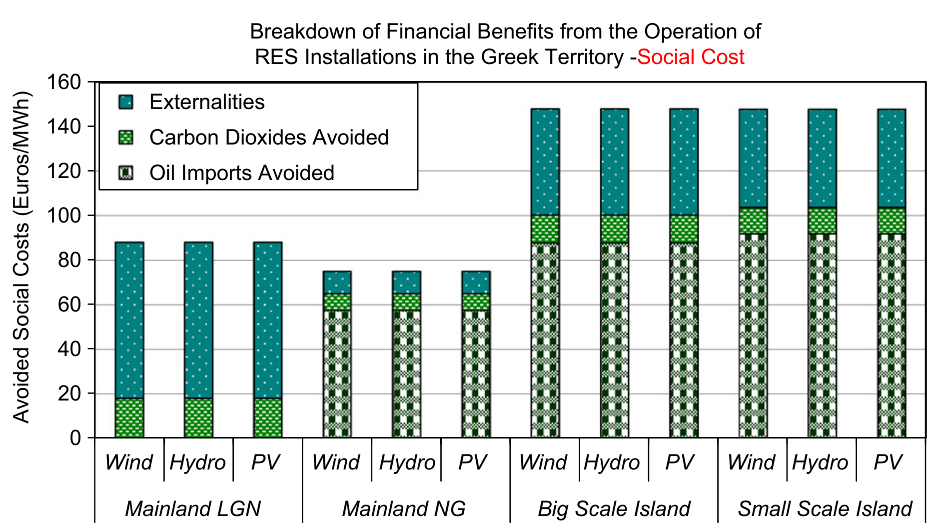

Fig. 10. Breakdown analysis of financial benefits from the avoidance of social costs for representative case studies.

regions where higher FITs along with higher CF values (e.g. wind energy case) and/or lower initial cost per kW installed (in comparison with the small island case where economies of scale and more serious infrastructure adequacies increase the specific purchase plus installation cost) configure the final result. Besides that, owed to the higher revenues per MWh, PV applications present taxes that may even approach 20 €/MWh, while on the other hand, hydropower stations presenting higher specific costs than- and similar FITs with wind farms demonstrate the lowest taxable amount of revenues.

Moreover, avoidance of the TPS operation, shown in Fig. 9 and being dependent only on the area of investigation, is as expected identical among the three technologies. As a result, lignite-based power stations appear to be the least expensive, followed by the alternative of NG for the mainland, while concerning islands, smaller scale implies higher production costs (see also Fig. 3). In fact, in the case study currently considered the production cost of the small island APS is found 5–10 times greater than the respective of the mainland stations, thus comprising the critical factor for the outcome of the cost–benefit analysis of these installations, while service period prolongation of the local APS (*other cost contribution* in the figure) in the case of islands, although minor should also be mentioned (see also Eq. (9)).

Analysis of benefits is completed by the social costs' breakdown (Eq. (19)), including the sub-benefits of avoiding energy imports, carbon dioxide emissions and externalities related with the use of fossil fuels for electricity generation purposes (Fig. 10). Due to the indigenous character of lignite the first of the terms mentioned above is eliminated in the first mainland case, nevertheless the total cost avoided is found to be greater than the corresponding NG case. Actually, heavy CO_2 emissions and severe environmental impacts of lignite power stations on a life cycle basis obscure the imports of NG [48], which, however, correspond to 70% of the total cost in the first mainland case. On the other hand, lower emission factors and less environmental impacts caused by NG power station lead to a total of 75 €/MWh, or 13 €/MWh less than the lignite case. On the other hand, oil-based generation adopted in island grids of the Greek region is found responsible for extreme values of all parameters considered, with the cost of oil imports corresponding to 60% of the total 147 €/MWh.

7.4. Break-even feed-in-tariffs (BEFITs)

Acknowledging the imbalance between costs and benefits, revealed in the previous paragraphs, an attempt is first made to determine the break-even point (Eq. (30)), based on the variation of existing FITs. In this context, in Figs. 11 and 12 one may obtain the BEFITs, either considering an initial cost subsidy ($\gamma > 0$) or not ($\gamma = 0$), as well as a comparison of the break-even values with the existing FITs. As expected, the higher BEFITs correspond to the technology with the highest net benefit, i.e. wind energy, while the exact opposite result is valid for PV installations demonstrating

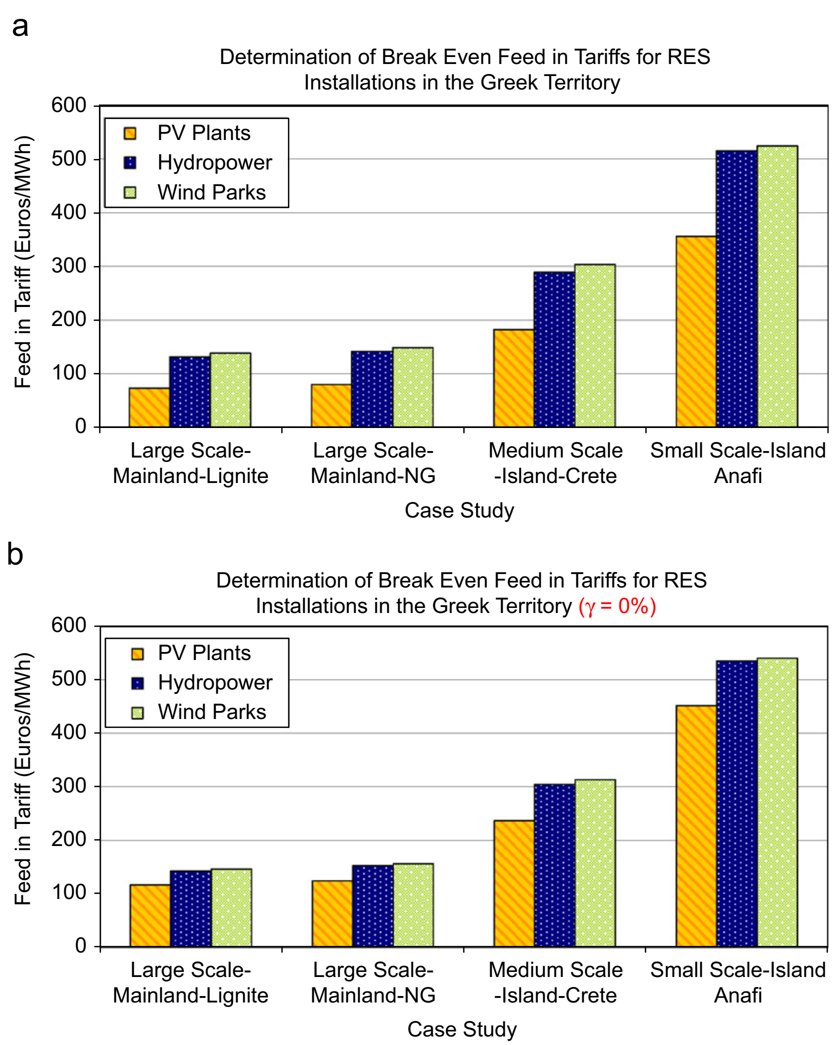

Fig. 11. Break-even feed-in-tariffs for representative case studies, with (a) and without (b) initial cost subsidy.

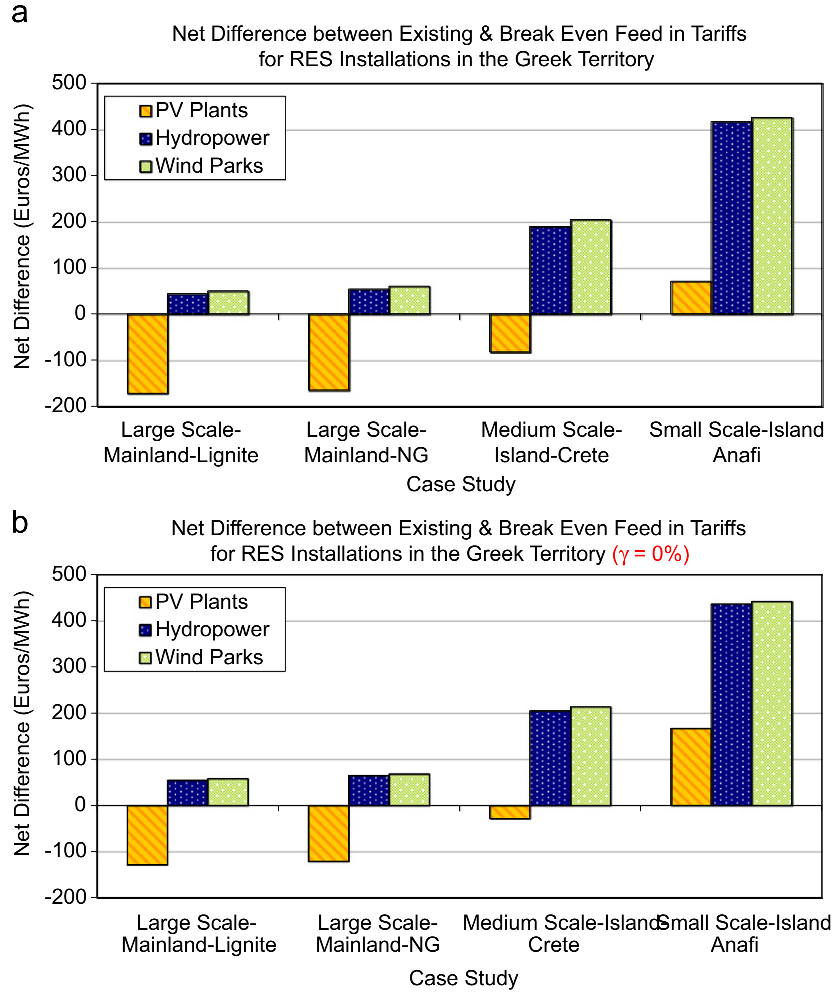

Fig. 12. Break-even vs existing feed-in-tariffs for representative case studies with (a) and without (b) initial cost subsidy.

BEFITs that in the case of mainland correspond to less than 55% of the respective wind energy BEFITs.

Accruing from the maximization of net benefits in the case of small island regions, it is impressive to see that although kept slightly above 350 €/MWh for PV applications, BEFITs may even reach or exceed 500 €/MWh for hydropower and wind energy installations (Fig. 11). By zeroing the initial cost subsidy, wind power and hydropower stations are only faintly influenced, while due to their capital intensity, PVs are largely affected with the mainland BEFITs found above 100 €/MWh and the island ones exceeding 235 €/MWh and 450 €/MWh (big and small islands, respectively).

By comparing the results obtained with the existing FITs (Fig. 12), one has the opportunity to determine the corresponding net difference. Negative values imply that in order for the State to achieve break-even between costs and benefits, reduction of the existing FITs is required, while furthermore, i.e. in the case of zero initial cost subsidy, positive values imply that the State may test various scenarios of different initial cost subsidy and FIT values, not possible in cases of negative net difference. In this context, the existing FITs of PV applications are higher than the respective BEFITs, except for the small-scale island case, while it is interesting to see that due to the appreciable impact that zeroing of the initial cost subsidy has on the PV BEFITs, the BEFIT of the big scale island case is approximately equal to the corresponding FIT, i.e. 264.85 €/MWh.

On the other hand, if the initial cost subsidy is not zeroed, the net difference may even exceed −150 €/MWh. Contrariwise, wind energy and hydropower stations present a net difference that may be found in the order of 400 €/MWh, clearly showing the beneficial characteristics of these installations for the Greek society. Actually, it is only in the case of the mainland (mostly lignite) and wind energy–hydropower applications that the existing FITs are somewhat near the respective break-even values, meaning that the State support plan may be considered as justifiable for both contributing ends (i.e. the society and the private investor).

7.5. Investigation of the entire PV application range

Due to the different FITs concerning PVs (see also Tables 1 and 3), depending on both the size of the installation and the area of application, it is interesting to also examine two additional scenarios that could not be included in the initial evaluation of all three technologies, mainly due to comparison purposes. The two additional cases (three last columns of Table 3) concern two medium size PV plants (<5 MW), the first installed on the mainland and the second on a big island region, with results obtained given in Figs. 13–15, where one may also encounter the results of the rest of PV applications already examined, again for comparison purposes. As one may see (Fig. 13), financial benefits are slightly affected due to the marginal increase of taxes, as a result of the increased FITs (plus 20 €/MWh). The impact of the new FITs is demonstrated more clearly in Fig. 14, where the increase of 20 €/MWh is recorded in the State support of both the mainland and the big island cases. In fact,

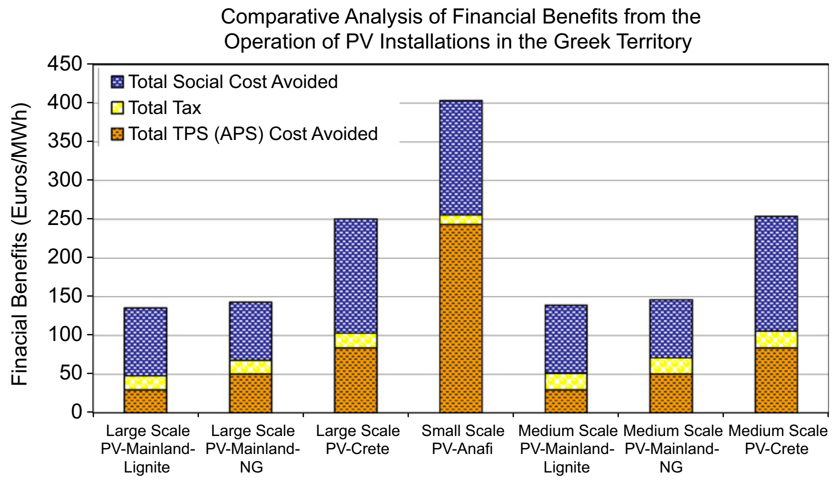

Fig. 13. Breakdown analysis of social benefits for representative PV case studies.

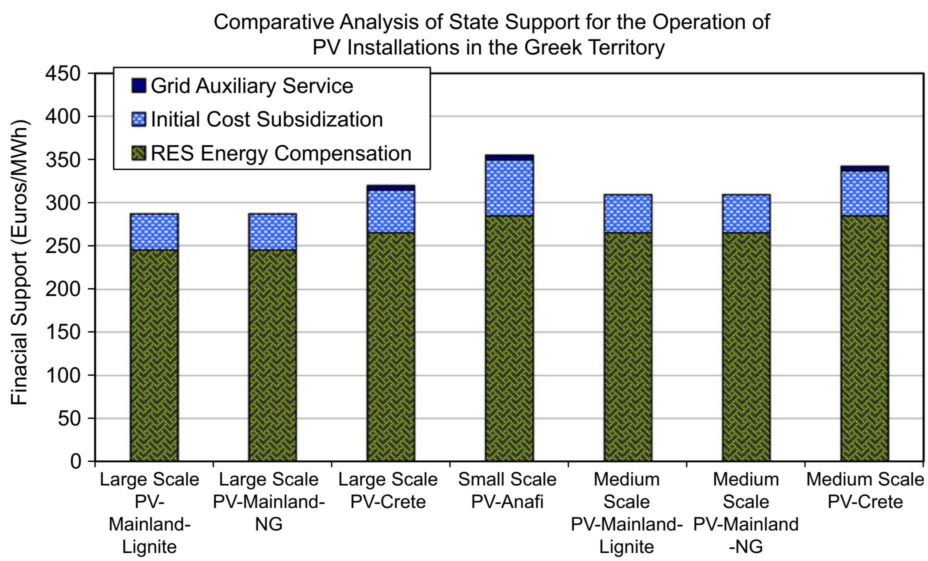

Fig. 14. Breakdown analysis of social support (costs) for representative PV case studies.

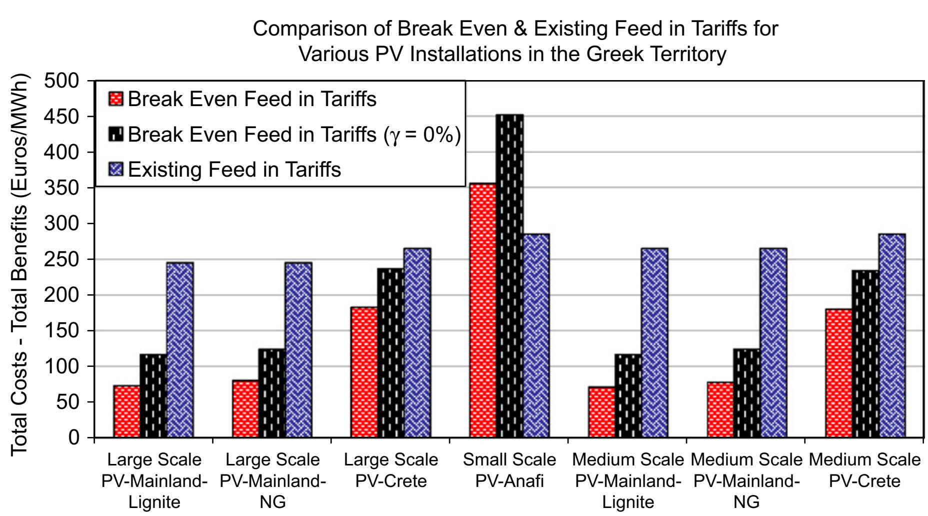

Fig. 15. Break-even vs existing feed-in-tariffs for representative PV case studies.

it is interesting to see that total costs of the medium size PV installation for the big island case approach the respective amount of the small size installation for the small island case (in the order of 340–350 €/MWh). As a result, in both cases examined, BEFITs are faintly reduced either for $\gamma > 0\%$ or for $\gamma = 0\%$ (Fig. 15), this implying a greater net difference (negative) with the existing FITs, i.e.

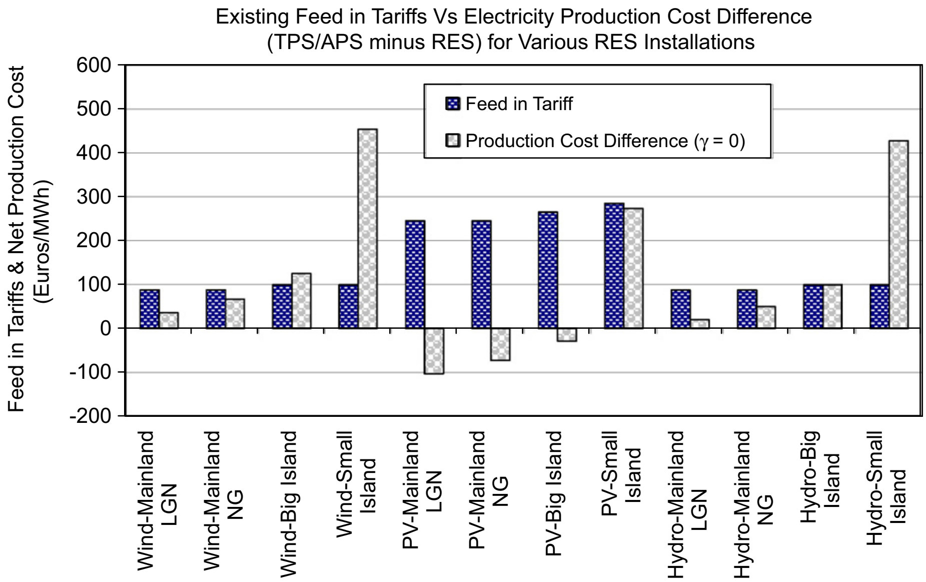

Fig. 16. Comparison of feed-in-tariffs with the electricity production cost difference "Δc" between TPSs/APSs and RES installations.

medium-scale PV projects of the mainland and big island areas appear marginally less effective than the respective large-scale projects.

7.6. Existing FITs vs electricity production cost difference

Finally, by applying the electricity production cost model, presented in Section 5, in Fig. 16 a comparison of results obtained (see also Eq. (28)) with the respective FITs is provided. Actually, the comparison attempted concerns the net difference "Δc" (for zero initial cost subsidy) between the electricity production cost of the TPS/APS station and the electricity production cost of the respective RES application on the one hand, and between the former and the existing FITs on the other hand. In this regard, there are two possible outcomes: either the net difference is found inferior to the FIT provided by the State (i.e. $\Delta c < p_0$) or the opposite (i.e. $\Delta c > p_0$). In the first case, State support yields that benefits accruing from the operation of RES stations do not only correspond to the reduction of the electricity production cost, while in the opposite case it seems that social support fails to compensate the investor even at the strictly financial level of electricity production cost. In this context, both wind energy and hydropower mainland stations are favored with FITs that are higher than the production cost net difference, while the situation is marginally inversed in the case of big islands. On the other hand, the extreme electricity production cost of APSs in small island regions does not allow for the investor's compensation. Finally, PV applications presenting a negative production cost difference in all cases except for the small island scenario are at all times favored by extremely high FITs that only seem justifiable in the small island case.

8. Conclusions

Acknowledging the need for evaluating the support mechanisms for RES in Greece, an extensive cost–benefit analysis is carried out in the specific study, in terms of "social justice". For this purpose, a number of representative case studies considering the three main RES, i.e. wind energy (wind parks), hydropower (small hydropower plants) and solar energy (PVs), are investigated in detail, in order for the resulting imbalances between costs and benefits to become straightforward. In this context, the beneficial character of wind energy and hydropower is designated, while on the other hand, surcharging of the Greek State concerning the majority of PV applications (apart from certain small island cases) demonstrates the urgency for the exploitation of the local solar potential and the commercialization of the technology in the Greek market. Ruling out a more balanced (between technologies) support plan on the other hand socially condemns wind energy and hydropower, especially in the case of island projects, i.e. the area where social performance of all three technologies calls for at least a partial reform of the current support pattern. Considering the above, reform may be undertaken on the basis of modifying both the initial cost subsidy and the FITs currently applied, taking also into account the distinct characteristics among different regions of the Greek territory (e.g. different local RES potentials). Nevertheless, for the integration of the analysis presented, the impact of cutting down public support – wherever this is "socially just" – should also be investigated from the private investor point of view.

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